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Computation of evapotranspiration using crop simulation models and comparison with leaf area index from multiple sources

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Abstract

The study demonstrated the computation of evapotranspiration (ET) in cultivation of groundnut (*Arachis hypogaea*) through the application of crop simulation models, alongside a comparative analysis with leaf area index (LAI) from various sources. The cultivation period for groundnut was conducted during the calendar year 2023, during which 2 distinct growth patterns were noted, attributed to variations in environmental conditions. The study analyses the estimated evapotranspiration from AquaCrop model, utilizing crop coefficient (Kc) values in comparison with evapotranspiration data derived from satellite observations provided by the MOD16A2v061 product. Furthermore, LAI was measured through 3 methodologies: an empirical equation based on field data, the Li-Cor 2200 plant canopy analyzer and LAI calculations derived from cloud-free normalized difference vegetation index (NDVI). LAI obtained from Li-Cor 2200 instrument exhibited a higher degree of consistency in correlation with empirical LAI derived from ground observations. Conversely, LAI values calculated using the normalized difference vegetation index (NDVI) demonstrated a greater degree of variability, especially during times of cloud cover. The study emphasizes the relationship between LAI and ET and magnitude of LAI in amount of total evapotranspiration.

Keywords

Evapotranspiration; Leaf Area Index; Plant Canopy Analyser; Crop coefficient (Kc) values

Introduction

Evapotranspiration (ET) and leaf area index (LAI) are critical parameters in understanding vegetation health and agricultural productivity. ET represents the sum of evaporation from the soil and transpiration from plants, serving as a key indicator of water usage and stress in crops. LAI measures the leaf area per unit ground area, providing insights into the canopy structure and potential photosynthetic capacity of vegetation.

In modern agriculture, understanding ET and LAI is crucial for efficient water management, optimizing irrigation schedules and maximizing crop yields (1). Remote sensing technologies and satellite imagery enhance the monitoring of these parameters, allowing for precise and timely agricultural interventions and geographically larger areas (2). As climate change and water scarcity challenges intensify, the importance of ET and LAI in sustainable agricultural practices cannot be overstated, making them vital tools for ensuring food security and environmental resilience.

Materials and Methods

Study area

Tamil Nadu state is characterised by varied climatic features and natural resources all over the area. Villupuram district in Northern part of Tamil Nadu is not an exception. Groundnut, sesamum, sunflower are the major oil seeds that are grown in and around Villupuram district of Tamil Nadu. The rainfed groundnut experimental field “L14” is in Oilseeds Research Station, Tindivanam, located in Marakkanam block in Villupuram district of Tamil Nadu, focuses on growth parameters, soil characteristics and environmental modifications for growth and development of various oilseeds like groundnut. Though an oilseed, groundnut is a strong source of minerals, vitamins, fats and proteins (3). The study area is depicted in Fig. 1(a) and the aerial view of L14 field from Google Earth Pro is shown in Fig. 1(b)

In Marakkanam block of Villupuram district, TMV-14 variety of groundnut is predominant. The block majorly followed sowing of this variety in Margazhipattam season during the period of December and January. For their special characteristics, 2 different groundnut seasons were practiced in L14 field of Oilseeds Research Station, Tindivanam. The crop details were described in Table 1.

Weather

Weather parameters for study area were retrieved from NASA POWER. On average, the aerodynamically rough surface, the study area received extremely heavy rainfall of 9.24 mm on November 2023, followed by 5.25 mm on September 2023. A moderate rainfall was received during May 2023 and August 2023 as 3.52 mm and 3.46 mm respectively. On the same hand, maximum temperature attained during November 2023 is 29.69 °C which is least of all month on an average. Similarly, the relative humidity was higher during November 2023 as 86.94 %. The tropical crop requires warm weather ranging from 30 °C – 35 °C in the vicinity (4). All the other weather parameters over Oilseeds Research Station, Tindivanam were depicted in Table 2 and Fig 2.

Evapotranspiration

Evapotranspiration is a combined process of evaporation and transpiration occurring in cropped and other land use surfaces. The water deficit condition beyond tolerable limit impacts crop productivity (5). Normally, Evaporation is the main way through which the water is lost. But as when the crop grows, the surface of the soil through which evaporation occurs is decreased because of the growth of the canopy and hence leaf area. This implies that, evaporation occurs during initial stage of crop development, as the growing period increases transpiration becomes the main process. Evapotranspiration is expressed in millimetres (mm) per unit time.

(i) Crop Simulation Model

AquaCrop is a crop growth model developed by land and water division of Food and Agriculture Organisation (FAO). This model addresses food security and assesses the impact of environment and climatic conditions on crop

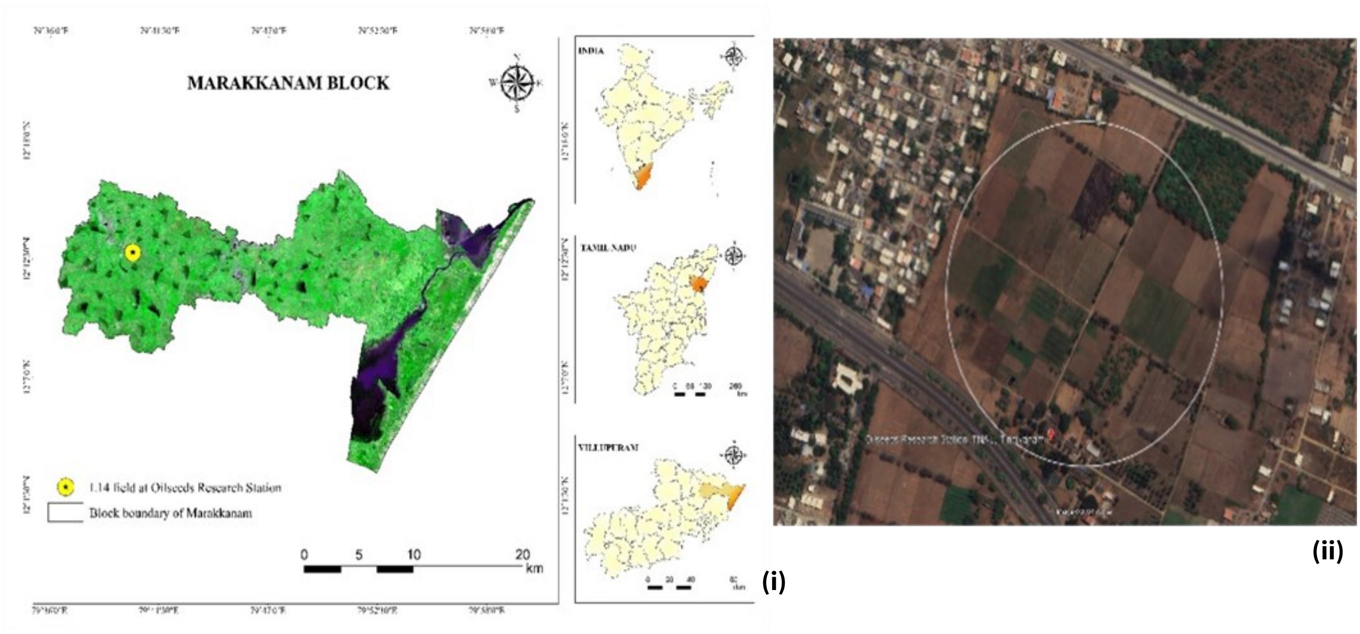

Fig. 1. (i) Study area map of L14 field in Oilseeds Research Station, Tindivanam (ii) Aerial view of L14 field from Google Earth.

Table 1. Details of groundnut cropping season.

	Season	Field number	Variety	Sowing date	Harvest date	Duration
(a)	Season - 1	L14	TMV-14	03.01.2023	08.05.2023	126 days
(b)	Season - 2			05.12.2023	13.04.2024	132 days

Table 2. Weather parameters prevailed in Oilseeds Research Station during 2023-2024.

Month	Minimum temperature (°C)	Maximum temperature (°C)	Mean temperature (°C)	Solar radiation (MJ/m²)	Relative humidity (%)	Wind speed (m/s)	Rainfall (mm)
Jan-23	18.85	29.15	24.00	17.75	77.61	2.44	0.13
Feb-23	19.59	32.87	26.23	21.87	69.01	2.23	0.36
Mar-23	22.70	35.26	28.98	21.91	67.25	2.46	1.18
Apr-23	25.13	37.86	31.50	23.12	60.87	2.35	0.70
May-23	26.37	36.31	31.34	20.83	67.76	2.15	3.52
Jun-23	26.05	35.79	30.92	19.70	64.94	2.56	3.05
Jul-23	24.97	35.10	30.04	17.51	66.26	2.97	3.30
Aug-23	25.93	35.68	30.81	20.50	66.52	2.06	3.46
Sep-23	24.37	33.32	28.85	20.24	75.74	2.36	5.25
Oct-23	24.14	33.22	28.68	18.55	76.25	1.73	1.98
Nov-23	23.81	29.69	26.75	13.96	86.94	2.28	9.24
Dec-23	21.81	29.08	25.45	12.92	85.79	3.06	2.61
Jan-24	20.60	29.62	25.11	16.62	80.67	2.50	2.39
Feb-24	21.58	33.30	27.44	21.25	72.76	2.52	0.02
Mar-24	22.86	37.15	30.01	23.36	60.55	2.29	0.03
Apr-24	25.66	40.13	32.90	25.33	57.75	2.50	0.08

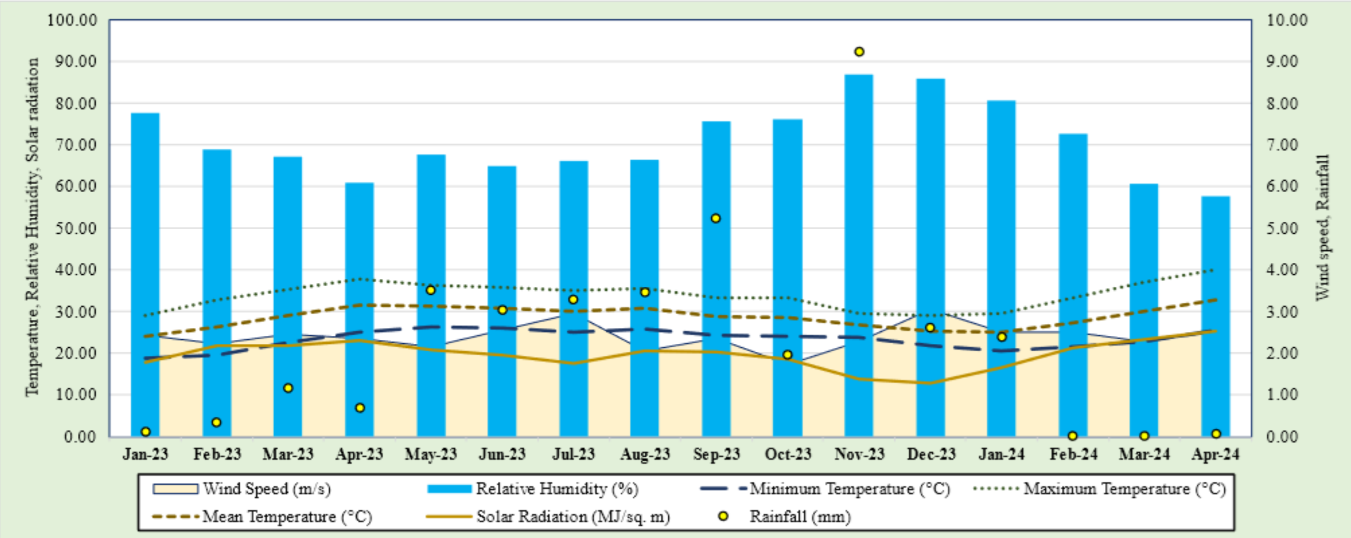

Fig. 2. Weather prevailed in Oilseeds Research Station, Tindivanam.

production. As the name suggests, AquaCrop simulated yield is a function of crop-water need and water consumption, under varied environmental conditions like rainfed, irrigated, surplus supplies, deficit conditions and actual proper conditions.

The model performs based on transpiration and water need of the crop to produce bio-mass with crop-specific parameters. Integrating environmental and climatic conditions into the model leverages the model to simulate the actual environmental conditions to produce the actual yield or biomass. The consumptive use of water under standard conditions can be simulated based on the climatic conditions like precipitation (mm), temperature conditions (°C), relative humidity (%), wind speed (m/s) and solar radiations (MJ/m²).

The simulations run under predefined climatic parameters with higher accuracy to produce several output parameters including reference evapotranspiration (ETo). Based on the input parameters we provide, the frequency of the output parameters also varies from daily to 10-days or even monthly frequency (6). A study identified balanced water environment in Apple orchards are must for sustainable development (7). A relationship between leaf area index, amount of evapotranspiration and crop coefficient value was discovered in Loess Plateau, China.

(ii) Satellite Products – MOD16A2

MOD16A2v061 (MODIS-16A2 Version 6.1) is an 8-days composite dataset available at 500 m spatial resolution. MOD16, an open-source satellite dataset is collected based on the Penman-Monteith equation, which includes inputs of daily meteorological data along with MODIS remotely sensed data products such as vegetation property dynamics (NDVI), land surface temperature (LST), albedo and land cover (8, 9).

Leaf Area Index

Leaf surface area determines the health of the plant. An increase in leaf area causes higher amount of carbon gained in photosynthesis and water loss through transpiration, both impacting crop yield (10). Leaf area index can be calculated through different ways.

LAI using empirical equation

LAI using plant canopy analyzer (Li-Cor 2200)

Spatially derived LAI using normalized difference vegetation index

(i) LAI using empirical equation

Density of plant canopy can be determined by leaf area index from empirical calculation using the equation

$$LAI = \frac{\text{Total Leaf Area}}{\text{Ground Spacing}} \quad \text{(Equation 1)}$$

(11)

Where, Leaf area = Leaf length x Leaf breadth x *K*

Area of single leaf is given by leaf length x leaf breadth x *K* (*K*=0.7). An average sized leaf is selected for area calculation and multiplied by total number of leaves. The area of leaf covered by ground area is the actual leaf area index.

(ii) LAI using Plant Canopy Analyzer (Li-Cor 2200)

Leaf area index measurement using Li-Cor 2200 is non-destructive way with higher accuracy. The leaf area index (LAI) and other canopy parameters are computed by LAI-2200C using light measurements obtained using a "fish-eye" LAI-2250 Optical Sensor known as "wand" (12). The sensor is equipped with high-precision optical components including optical filters, light sensors and lenses (13).

Assumptions

Certain assumptions are made in order to calculate foliage density and orientations. As long as adhering to these assumptions, accuracy of these measurements is high.

(i) The foliage is black i.e., below-canopy readings do not reflect or transmit any radiation.

(ii) The foliage is randomly distributed.

(iii) The distance between sensor and nearest leaf measured above it, must be at least 4 times the leaf breadth

(iv) The foliage has random azimuthal orientations.

Principle

A radiative transfer model in vegetative canopies is used to calculate leaf area index from measurements taken above and below the canopy to determine canopy light interception at 5 zenith angles.

The amount of foliage in vegetative canopy can be deduced from measuring the velocity of light from canopy to foliage as the sensor is facing up the sky. Foliage orientation can be calculated by measuring this attenuation at several angles from zenith. As a calibration, the attenuation of diffuse sky radiation is measured through optical sensor. (From Li-Cor 2200 Plant Canopy analyser Manual)

(iii) Spatially derived LAI using Normalized Difference Vegetation Index

Leaf area index and normalized difference vegetation index are related exponentially. A spectral index developed from remote sensing data implies a ratio between inter-bands, with reflectance on each electromagnetic spectrum. These spectral indices depict plant biophysical and biochemical characters. Andalibi, Ghorbani (14) stated that,

$$LAI = 0.57 \times e^{(2.33 \times NDVI)} \quad \text{(Equation 2)}$$

To get LAI, NDVI can be derived from sentinel-2, open-source, optical satellite data, by using the equation,

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad \text{(Equation 3)}$$

The derived NDVI can be fitted into Equation 2, to get leaf area index for the specific period.

Results

Evapotranspiration

(i) Crop Simulation Model

The accuracy metrics and applicability of AquaCrop model for estimation of evapotranspiration is high restricted with input parameters over the area and period (15). The input parameters for AquaCrop model we provide were maximum temperature (°C), minimum temperature (°C), mean temperature (°C), rainfall (mm), relative humidity (%), wind speed (m/s) and solar radiation (MJ/m^2). The daily weather parameters retrieved from NASA POWER were incorporated into AquaCrop model for the period 01st January 2023 to 30th April 2024, covering both cropping seasons.

The model simulated actual field conditions and produced output parameters including reference evapotranspiration (ETo). On the end of simulation, a climate file, reference evapotranspiration (ETo) file and temperature files were saved as output file. As a result, daily ETo is obtained for period defined.

To estimate actual evapotranspiration (ETa) of groundnut from reference evapotranspiration (ETo), we use the formula,

$$\text{Crop coefficient (Kc)} = \frac{\text{Crop Evapotranspiration}}{\text{Reference Evapotranspiration}}$$

(Equation 4)

where, evapotranspiration is denoted by the unit (mm/day) and crop coefficient is dimensionless(16, 17). Daily reference evapotranspiration over Oilseeds Research Station, Tindivanam derived using AquaCrop model is depicted in the Fig. 3. The total reference evapotranspiration for groundnut based on the season is described in the Table 3.

The crop coefficient for each crop follows a standard pattern (1) and the kc values used here are suggested by Food and Agriculture Organisation (Fig. 4). From Equation 4, daily actual crop evapotranspiration (ETa), was derived from reference evapotranspiration and crop coefficient values (18). Actual evapotranspiration (ETa) during the year 2023-2024 was depicted in the Fig. 5. The season-wise crop-coefficient values and actual evapotranspiration was described in the Table 3 and Fig. 6. A study stated that the Kc curve is a simple representation for implying crop

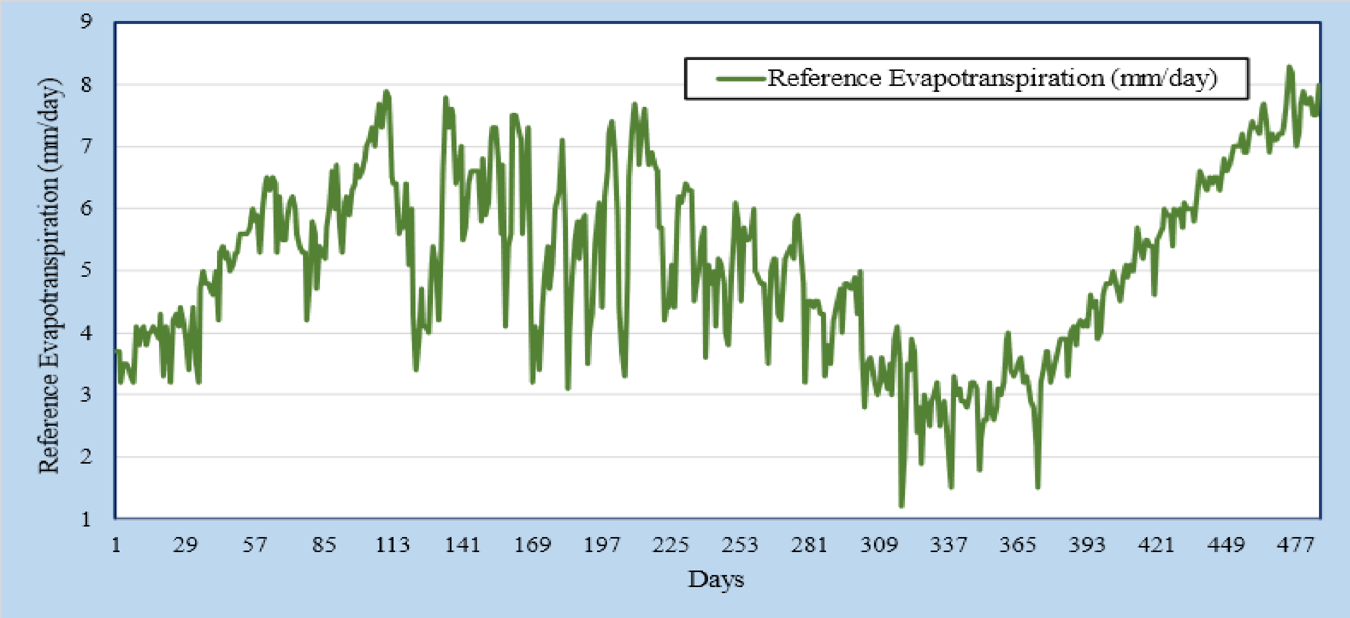

Fig. 3. Daily reference evapotranspiration from AquaCrop model during 01.01.2023 to 30.04.2024 over L14 field in Oilseeds Research Station, Tindi-

Table 3. Stage-wise amount of evapotranspiration for season 1 and season 2**.**

Growth Stage	Days after sowing	Crop coefficient from FAO	Mean actual evapotranspiration (mm/day)		Total actual evapotranspiration (mm)	
			Season 1	Season 2	Season 1	Season 2
Initial stage	16	0.4	1.49	1.14	23.96	18.32
Development stage	45	0.7	3.04	2.28	88.27	66.22
Mid stage	75	0.95	5.48	4.28	164.44	128.53
Late stage	95	0.7	3.99	3.94	79.8	78.89
Harvest stage	128	0.55	3.33	3.74	103.4	134.75

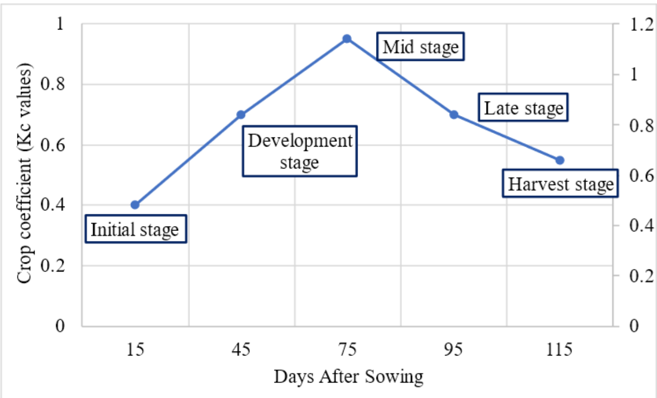

Fig. 4. Crop coefficient (Kc values) from FAO.

specific impact on amount of evapotranspiration (19).

(ii) Satellite Products – MOD16A2

MOD16A2 products were the direct product of amount of total evapotranspiration with a scale factor 0.1. The product has a spatial resolution of 500 m i.e., the moderate resolution product of 500 m provides evapotranspiration covering the area of 500 m. The amount of area covered by a pixel may include different land covers, obviously altering the amount of evapotranspiration. Such moderate resolution product provides a less accurate data, required for field/plot area. The total amount of evapotranspiration for each 8-days

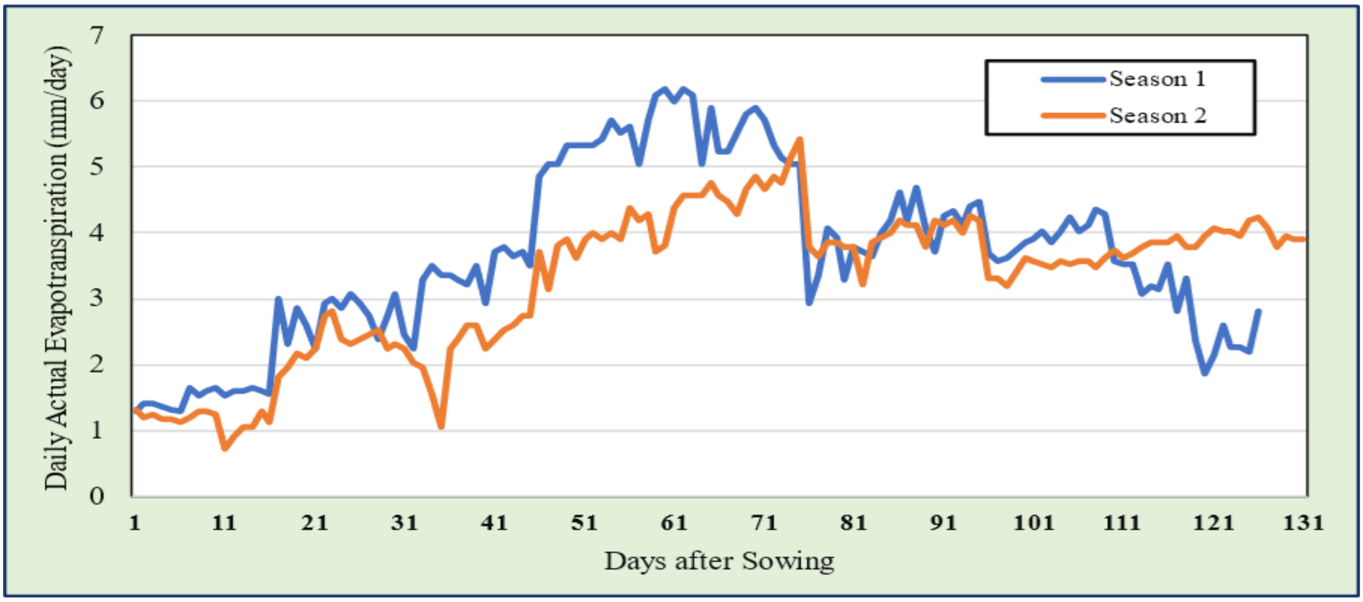

Fig. 5. Daily actual evapotranspiration during the cropping season over L14 field in Oilseeds Research Station, Tindivanam.

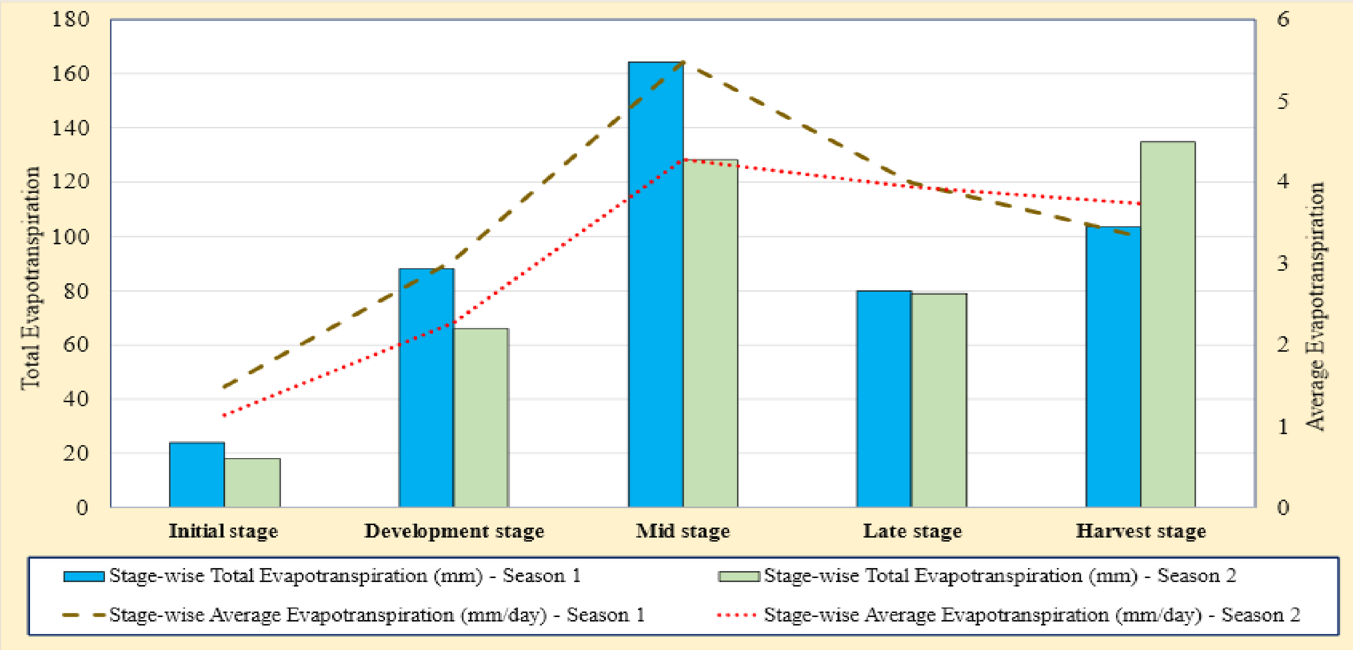

Fig. 6. Stage-wise amount of evapotranspiration during season -1 and season -2.

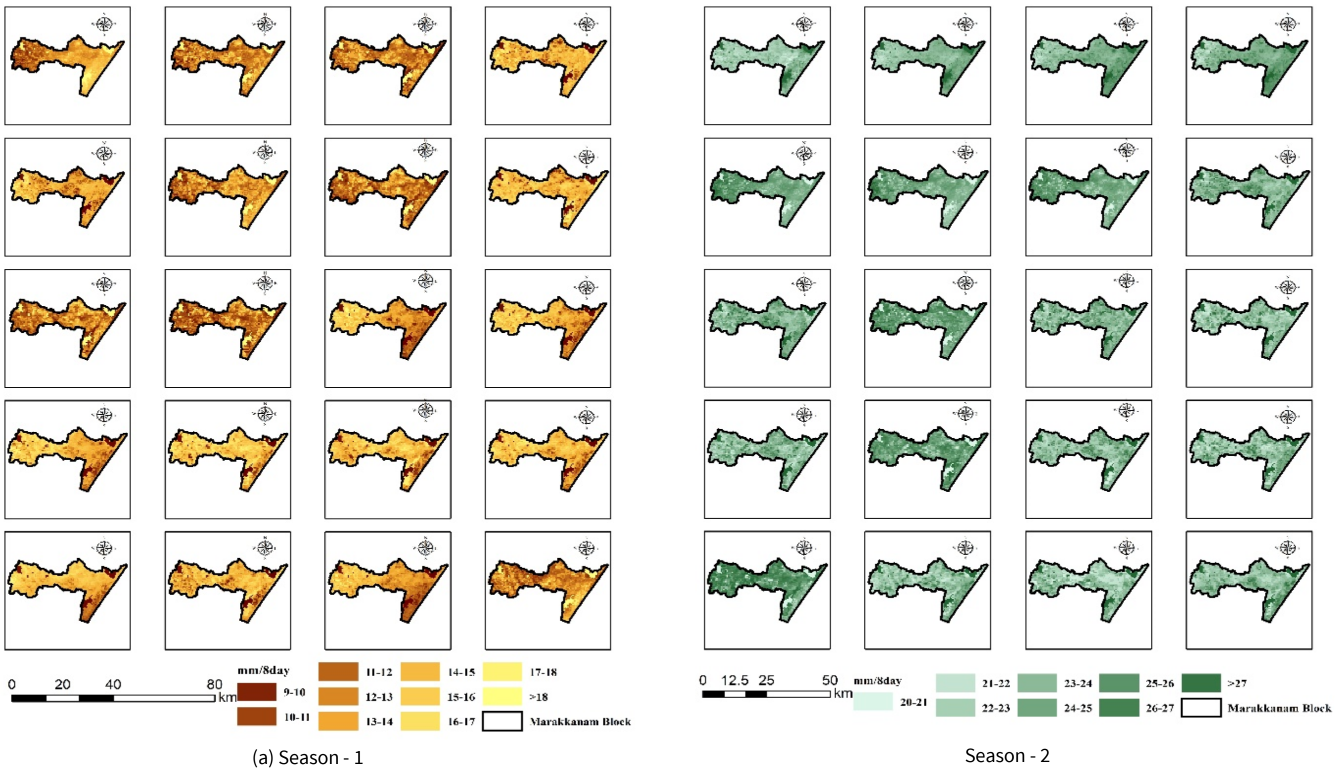

Fig. 7. MOD16A2 - 8-days composite evapotranspiration data over Marakkanam block.

covering the entire Marakkanam block during both the cropping seasons were shown in the Fig. 7.

The total amount of evapotranspiration for the groundnut field derived from MOD16A2 was found to be (a) 230.1 mm (b) 286.6 mm during the entire cropping period i.e., from sowing date to harvest date.

Leaf Area Index

(i) LAI from empirical equation

The crop biometric characters like number of leaves, Crop height, leaf length and width (in cm) were collected to calculate leaf area index (LAI) manually from the Equation 1 calculated and measured using Li-Cor (2200) Plant canopy analyzer were collected for the entire season from sowing to harvest for every 10-15-days.

On the entire field, 5 different replications were taken into calculation as a representative sample of entire field. Table 4 shows mean LAI from 5 different samples collected on specified dates.

(ii) LAI from Plant Canopy Analyzer (Li-Cor 2200)

Li-Cor 2200 measures light blocking objects from the base. In such a case, LAI value here is density of foliage. Measurement of multiple transmissions can be combined by averaging natural logarithms to compute leaf area index. A sample observation of LAI using Li-Cor 2200 is

Table 4. LAI using empirical equation in L14 groundnut field from two different cropping seasons.

Sl. No	Date of observation	Days after sowing	Crop height (cm)	Number of leaves	Leaf length (cm)	Leaf width (cm)	LAI using empirical equation
				Season - 1			
1	21.01.2023	18	9.30	28	3.40	1.70	0.38
2	01.02.2023	30	12.62	36	3.70	1.90	0.59
3	15.02.2023	45	16.12	81	4.00	2.40	1.81
4	02.03.2023	60	33.48	97	4.70	2.60	2.77
5	16.03.2023	75	58.62	115	5.80	3.00	4.67
6	03.04.2023	90	73.08	122	6.10	3.60	6.25
7	12.04.2023	100	74.42	138	7.10	3.30	7.54
8	22.04.2023	110	77.10	156	7.10	3.20	8.27
				Season - 2			
1	20.12.2023	15	7.96	30	3.14	1.6	0.35
2	05.01.2024	30	12.48	38	5.2	2.82	1.30
3	23.01.2024	45	15.96	80	4.26	2.86	2.27
4	01.02.2024	55	30.00	129	6.02	2.94	5.33
5	16.02.2024	70	42.60	168	5.74	2.18	4.91
6	02.03.2024	85	58.20	158	5.78	2.52	5.37
7	15.03.2024	100	67.34	155	7.14	3.3	8.52

Fig. 8. Leaf area index measurement using Li-Cor 2200 on 02.03.2023 (60 DAS).

Table 5. LAI using Li-Cor 2200 in L14 groundnut field from two different cropping seasons.

Sl. No	Date	Days after sowing	LAI from Li-Cor (2200)
		Season - 1	
1	21.01.2023	18	0.45
2	01.02.2023	30	0.62
3	15.02.2023	45	1.67
4	02.03.2023	60	3.53
5	16.03.2023	75	4.91
6	03.04.2023	90	5.42
7	12.04.2023	100	6.14
8	22.04.2023	110	7.96
		Season - 2	
1	20.12.2023	15	0.63
2	05.01.2024	30	1.90
3	23.01.2024	45	3.11
4	01.02.2024	55	3.37
5	16.02.2024	70	3.93
6	02.03.2024	85	5.01
7	15.03.2024	100	6.33

depicted in Fig. 8. The measurement of LAI using Li-Cor 2200 from sowing to harvest for both seasons is shown in Table 5.

(iii) Spatially derived LAI using Normalized Difference Vegetation Index

LAI was derived from NDVI from the passes throughout the cropping period. NDVI was generated from sentinel-2 optical satellite data. The sentinel-2 data acquisition dates were displayed in the Table 6. Spatially derived LAI values from cloud-free NDVI for entire groundnut cropping season of L14 field in Oilseeds Research Station, Tindivanam was displayed in the Fig. 9 and their LAI values are shown in the Table 6.

A comparison between LAI values from each source

Table 6. LAI using cloud-free NDVI from sentinel-2 in L14 groundnut field from two different cropping seasons.

Sl. No	Date	Days after sowing	LAI from cloud-free NDVI
		Season - 1	
1	20.01.2023	17	0.46
2	04.02.2023	33	0.71
3	14.02.2023	44	1.05
4	01.03.2023	59	1.47
5	16.03.2023	75	3.87
6	05.04.2023	92	6.1
		Season - 2	
1	21.12.2023	16	0.62
2	05.01.2024	30	1.21

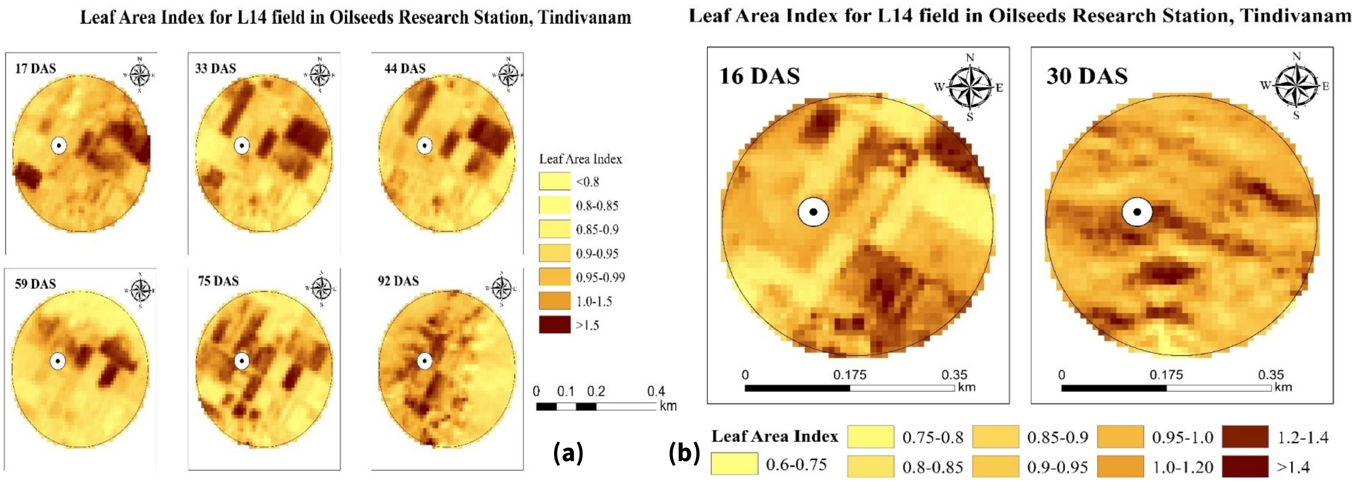

Fig. 9. Spatially derived leaf area index using NDVI from sentinel-2 from sowing to harvest for two different cropping seasons.

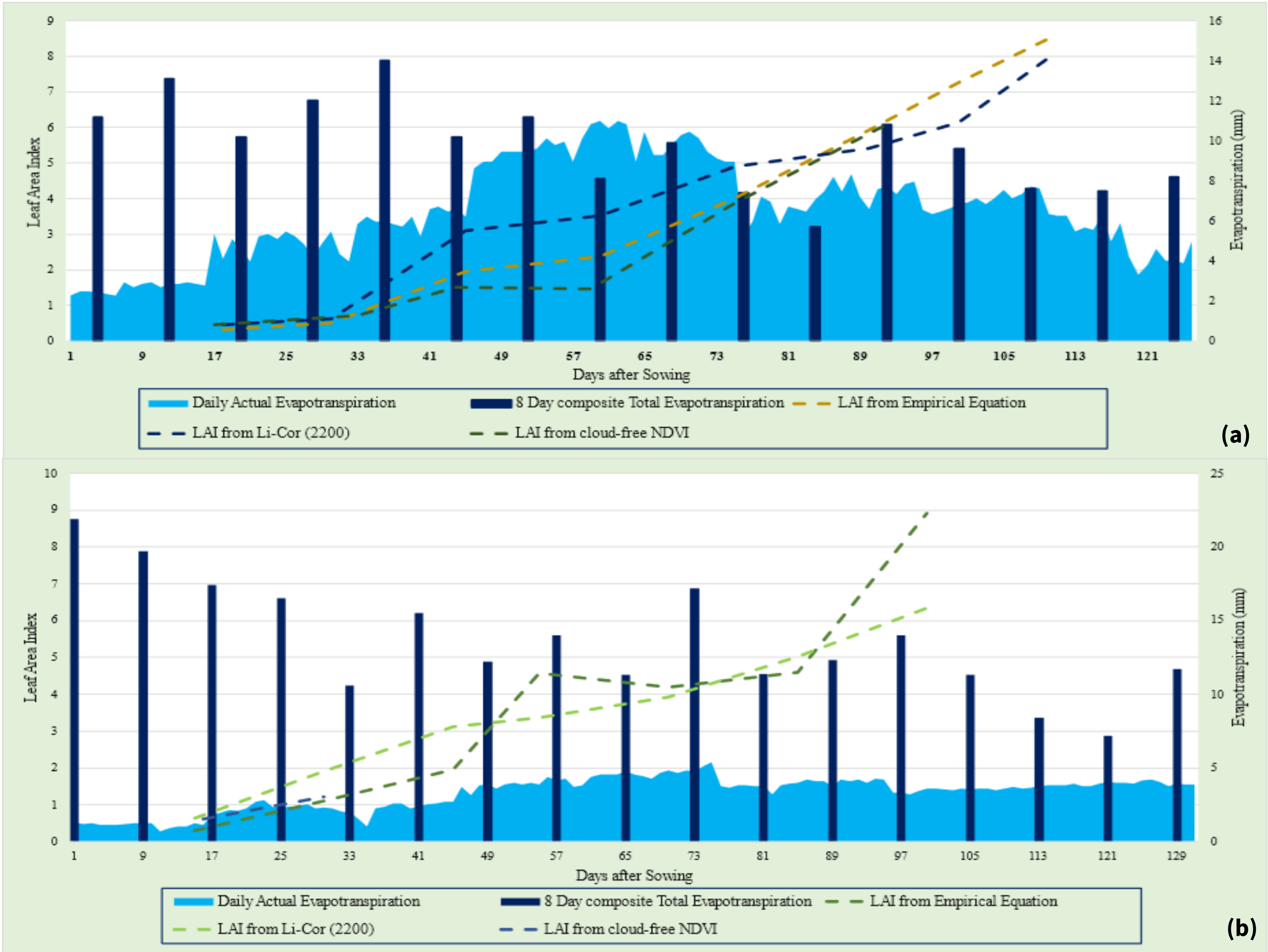

Fig. 10. Comparison of amount of evapotranspiration and leaf area index from various sources during two different cropping seasons.

and amount of evapotranspiration from 8-days composite MOD16A2.v061 and calculated using reference evapotranspiration for season-1 and season-2 were shown in the Fig. 10.

Relationship between Leaf Area Index and Evapotranspiration

From the study, among the various factors influencing the amount of ET, plant specific parameter like LAI impacts to extreme level. Certain factors like plant type, soil moisture, weather characteristics and management practices impact the relationship between LAI and ET. Leaf area index generally means area of leaf in a plant over the ground area.

The relationship between ET and LAI is pivotal; a higher LAI typically indicates more leaf surface area for transpiration, leading to increased ET. Understanding the relationship between LAI and ET is crucial for effective water management in agriculture, forestry and ecosystem conservation. It helps in predicting water requirements, planning irrigation schedules and assessing the impact of vegetation changes on the water cycle. This interaction underscores the health and vigor of crops, as adequate transpiration is essential for nutrient uptake and cooling the plant. Conversely, reduced LAI can signal stress or poor health, resulting in lower ET rates and diminished crop performance. A study evaluated three different models for estimation of evapotranspiration (20). All 3 models use leaf area index as an input, implying that there is a relationship between leaf area index and evapotranspiration.

An increase in leaf area index leads to higher evapotranspiration because of increased surface area for transpiration. Dense canopies over the plant area can shade the soil, thereby reducing soil evaporation but also significantly increases overall evapotranspiration through transpiration. Another study found that the vegetation blocks the solar radiation reaches the ground (21). Based on this, they quantified evapotranspiration-induced cooling of vegetation through normalisation of latent heat flux of canopy.

On the other hand, low LAI leads to lower ET implying minimal surface area for transpiration. Additionally, more exposed soil to solar radiation increased soil evaporation, but the overall ET is less when compared to high LAI scenarios. An increased LAI causes increased ET through increased surface area for transpiration, micro-climate near leaf surfaces from dense canopy. The increased surface area causes high solar radiation interception and heat dissipation by more leaves. The reliability on single parameter like leaf area index showed less accuracy for representation of soil characters like soil moisture, soil temperature and carbon flux (22).

Conclusion

The study highlights the critical roles of evapotranspiration (ET) and leaf area index (LAI) in assessing vegetation health and improving agricultural productivity, with a specific focus on the groundnut fields in Oilseeds Research Station, Tindivanam, Marakkanam block, Villupuram district, Tamil Nadu. ET is a key indicator of water usage and crop stress, while LAI, the ratio of leaf area to ground area, provides insights into canopy structure and photosynthetic capacity (23). Utilizing a combination of ground measurements, AquaCrop simulation models and MODIS satellite data, the study explores the intricate relationship between these 2 parameters.

Findings indicate a direct correlation between LAI and ET: higher LAI values lead to increased ET due to a greater leaf surface area available for transpiration. This is crucial during the crop's growth stages when transpiration becomes the dominant process over soil evaporation. Conversely, lower LAI values result in reduced ET, reflecting limited leaf surfaces for transpiration. This relationship is vital for effective water management and irrigation planning, enabling predictions of crop water requirements and timely agricultural interventions.

As climate change and water scarcity challenges intensify, understanding the relationship between ET and LAI becomes increasingly important. Effective monitoring and management of these parameters can help optimize irrigation schedules, improve crop yields and ensure sustainable agricultural practices (24). The study underscores that ET and LAI are not only vital for agricultural productivity but also for ensuring food security and environmental resilience in the face of global climate challenges.

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Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest among us.

Ethical issues: None.

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